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Contributions of Charm Physics to CKM Parameters

D.G. Cassel

Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, NY 14853

Determinations of CKM matrix elements are clouded by uncertainties in nonperturbative QCD parameters that relate measurable quantities to the underlying parton-level processes. A principal goal of the CLEO-c program is to provide precision measurements in the c-quark sector that will stimulate lattice QCD theorists to calculate relevant nonperturbative QCD parameters in this sector and to validate the calculations. This interaction between theory and experiment should build confidence in calculations of the parameters in the b-quark sector required for precision determinations of the CKM matrix elements $|V_{cb}|$, $|V_{ub}|$, and $|V_{td}|$.

1 Introduction and Motivation

Everyone at this workshop is all too aware that at least one nonperturbative QCD parameter that relates measurable quantities to the underlying parton-level processes stands between an experimental measurement and determination of a CKM matrix element. Progress in determining CKM matrix elements is already – or very soon will be – limited by uncertainties in these QCD parameters. Theoretical uncertainties totally dominate the $|V_{td}|$ error and – even with the relatively modest CLEO luminosities – they are significant in $|V_{cb}|$ and $|V_{ub}|$ errors. Experimental uncertainties will decrease significantly when the enormous BaBar and Belle data samples are fully understood and evaluated. Full exploitation of these data samples for determining CKM matrix elements will require substantial theoretical progress in developing reliable methods for calculating these nonperturbative parameters.

Lattice QCD (LQCD) shows promise of being a theory capable of calculating most of the required parameters to a precision of a few percent [1]. However, verification of these calculations will require comparison of LQCD results with a large number and wide variety of precision experimental measurements in the c- and b-quark sectors. Providing precise c-quark decay data to motivate and validate theoretical progress in nonperturbative heavy quark physics is a major focus of the CLEO-c program [2]. The other major focus – searches for glueballs – is not directly related to the subject of this workshop.

2 Determining $|V_{td}|$ from $B^0\bar{B}^0$ Mixing

Determination of $|V_{td}|$ from $B^0\bar{B}^0$ mixing is the extreme example of the mismatch between experimental and theoretical precision [3]. The measured mass difference due to $B^0\bar{B}^0$ mixing is related to $|V_{td}|$ by

$$\Delta m_d = \frac{G_F^2}{6\pi^2}\,\eta_{QCD}\,M_B f_B^2 B_B\, m_t^2\, F(x_t)\,|V_{td}|^2\,|V_{tb}|^2 \quad (1)$$

where Δm_d is the B^0 mass difference, G_F is the Fermi constant, η_{QCD} is a QCD correction factor, M_B is the B^0 mass, B_B is the B^0 bag constant, f_B is the B^0 pseudoscalar decay constant, m_t is the top-quark mass, and $F(x_t)$ is a known function of $x_t = m_t^2/m_W^2$. Everything in this expression is reasonably well known, except $|V_{td}|$, f_B, and B_B. Table 1 gives the principal contributions to the uncertainty in $|V_{td}|$ using parameters from the most recent Particle Data Group CKM review [4]. The contribution from the theoretical uncertainty in $\sqrt{B_B}f_B$ dominates the contribution from the Δm_d error by an order of magnitude and the contribution from the m_t error by nearly an order of magnitude!

Table 1. The principal sources of uncertainties in $|V_{td}|$ and their contributions to $\Delta|V_{td}|$. The values of $|V_{td}|$ and $\Delta|V_{td}|$ (in the lazy-L-shaped region of the table) have been multiplied by 10^3.

	Δm_d [ps^{-1}]	m_t [Gev]	$\sqrt{B_B}f_B$ [MeV]	$\lvert V_{td}\rvert$
Value	0.489 ± 0.008	166 ± 5	226 ± 36	8.44
$\Delta\lvert V_{td}\rvert$	$^{+0.06}_{-0.06}$	$^{+0.18}_{-0.18}$	$^{+1.5}_{-1.1}$	$^{+2.0}_{-1.4}$

2.1 Determining f_B

The factor $f_B|V_{ub}|$ occurs in the decay amplitude for the $\bar{b}uW$ vertex in leptonic B decay, illustrated in Figure 1. The decay width for leptonic B^+ decays is

$$\Gamma(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}\,M_B\,m_\ell^2\left(1 - \frac{m_\ell^2}{M_B^2}\right) f_B^2\,|V_{ub}|^2 \quad (2)$$

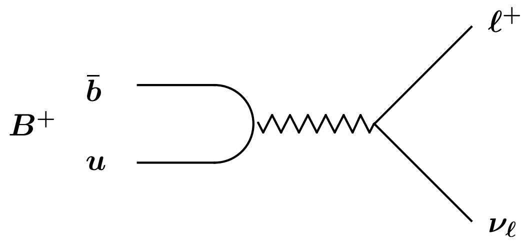

Figure 1. The Feynman diagram for $B^+ \to \ell^+\nu$ decay.

where M_B is the B^+ mass and m_ℓ is the ℓ^+ mass. Hence, measurement of $\mathcal{B}(B^+ \to \ell^+\nu_\ell)$ would determine $f_B|V_{ub}|$. However, there are serious problems with determining f_B this way. First, because $|V_{ub}|$ is very small, the leptonic branching fractions are also very small for a reasonable value (200 MeV) of f_B:

$\mathcal{B}(B^+ \to \mu^+\nu_\mu) \sim 3 \times 10^{-7}$

$\mathcal{B}(B^+ \to \tau^+\nu_\tau) \sim 6 \times 10^{-5}$.

Second, detection of these decays requires reconstruction of the neutrino(s) using the complete reconstruction of a tagging hadronic B decay. There are very many B decay modes with small branching fractions and small reconstruction efficiencies due to the necessity of reconstructing the D daughters from the B decays. Hence, in the foreseeable future, LQCD will certainly be required for precision estimates of f_B.

2.2 Determining $|V_{cb}|$ from Exclusive Semileptonic B Decay

Inclusive and exclusive $\bar{B} \to X\ell\bar{\nu}$ decay can be used to determine $|V_{cb}|$ and $|V_{ub}|$ [3]. The status of inclusive measurements of $|V_{cb}|$ – based on CLEO's recent measurements of some nonperturbative parameters using moments of $B \to X_s\gamma$ and $\bar{B} \to X_c\ell\bar{\nu}$ – are described elsewhere in this workshop [5]. Measurements of $|V_{ub}|$ are described in the 2002 CKM workshop [3] and in other reports in this workshop [6]. Hence, in this report I will concentrate on exclusive measurements of $|V_{cb}|$ and mention corresponding measurements of $|V_{ub}|$.

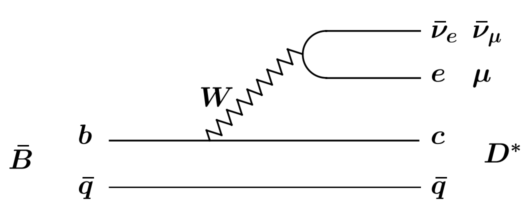

Figure 2. The Feynman diagram for $\bar{B} \to D^*\ell^-\bar{\nu}$ decay.

The Feynman diagram for $\bar{B} \to D^*\ell^-\bar{\nu}$ decay is illustrated in Figure 2. From Heavy Quark Effective Theory (HQET) and Isgur-Wise Symmetry, the differential decay width for $\bar{B} \to D^*\ell^-\bar{\nu}$ decay is

$$\frac{d\Gamma(w)}{dw} = \frac{G_F^2}{48\pi^3}\,\mathcal{G}(w)\,|V_{cb}|^2\,\mathcal{F}_{D^*}^2(w) \qquad (3)$$

with $w \equiv v_B \cdot v_{D^*} = \dfrac{\mathcal{E}_{D^*}}{M_{D^*}} = \dfrac{M_B^2 + M_{D^*}^2 - q^2}{2M_BM_{D^*}}$.

In these expressions, M_B and M_{D^*} are the masses of the B and D^*, v_B and v_{D^*} are the four-velocities of the B and D^*, $\mathcal{E}_{D^*}$ is the energy of the D^* in the B rest frame, $\mathcal{G}(w)$ is a known function of w, $\mathcal{F}_{D^*}(w)$ is an unknown form factor, and q^2 is the square of the invariant mass of the W or the $\ell\nu$ system.

Since everything else in Equation (3) is known or can be measured, the product $|V_{cb}|\mathcal{F}_{D^*}(w)$ can be measured. In particular – with sufficient data – the w dependence of $\mathcal{F}_{D^*}(w)$ can be determined accurately. However, to determine $|V_{cb}|$ we still need $\mathcal{F}_{D^*}(1)$ from theory. This quantity is constrained by HQET, $\mathcal{F}_{D^*}(1) \approx \eta_A[1 + \mathcal{O}(1/m_Q^2)]$, for large heavy quark masses and can be computed with LQCD. However, even with current experimental uncertainties [3, 7], the uncertainty in this parameter makes a significant contribution to the uncertainty in determining $|V_{cb}|$ by this method.

Determining $|V_{ub}|$ from exclusive $\bar{B} \to X_u\ell\bar{\nu}$ decays is even worse. We don't even have HQET and Isgur-Wise Symmetry to constrain the form factors and theoretical uncertainties dominate current measurements [8]. Hence, to measure $|V_{ub}|$, we need a reliable theory for the form factors $f(q^2)$ for these decays.

3 The CESR-c/CLEO-c Program

CLEO-c is a focused program of measurements and searches in e^+e^- collisions in the $\sqrt{s} = 3 - 5$ GeV energy region. The items in the program most relevant for this workshop are measurements of: absolute charm branching fractions, D meson semileptonic decay form factors, $|V_{cd}|$ and $|V_{cs}|$, and the decay constants f_D and f_{D_s}. Other items in the core CLEO-c program include: searches for new physics, *e.g.*, CP violation in D decay, rare D decays, and $D\bar{D}$ mixing without backgrounds from doubly suppressed Cabibbo decays; and QCD studies, particularly $b\bar{b}$ spectroscopy and searches for glue-rich exotic states (glueballs) [2].

The existing state-of-the-art CLEO III detector is a crucial element of this program [2]. It includes a central drift chamber for measuring the momenta of charged particles and identifying them via their energy losses (dE/dx), a CsI electromagnetic calorimeter for photon detection and electron identification, and a ring imaging Cherenkov detector (RICH) for charged

particle identification at higher momenta. The capabilities and performance of this detector represent substantial advances above those of other detectors that have operated in the charm threshold region.

3.1 CLEO-c Run Plan

The core CLEO-c program consists of four components, each expected to take about one year to complete. The anticipated data samples are:

- Prologue – $\Upsilon(nS)$'s $\gtrsim$1.2 fb^{-1} each
  - $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ – Completed
  - 10-20 $\times$ the previous world's data
- Act I– $\psi(3770)$ 3 fb^{-1}
  - 30 M $D\bar{D}$ events, 6 M tagged D's
  - 310×MARK III data
- Act II – $\sqrt{s} \sim 4.1$ GeV – 3 fb^{-1}
  - 1.5 M $D_s\bar{D}_s$ events, 0.3 M tagged D_s's
  - 480×MARK III data and 130×BES II data
- Act III – J/ψ – 1 fb^{-1}
  - 1 G J/ψ decays
  - 170×MARK III data and 20×BES II data

Taking data at the narrow Υ resonances is complete. Goals of this program include: precision measurement of matrix elements, Γ, and Γ_{ee} to compare with LQCD calculations; and $b\bar{b}$ spectroscopy studies including searches for η_b, h_b, and $\Upsilon(1D)$ states. The $\Upsilon(1D)$ has already been observed in these data [9].

At the time of this workshop we are in the midst of a shutdown to replace the CLEO III silicon vertex detector with a low-mass gaseous vertex detector and to upgrade CESR for high luminosity in the charm threshold region.

3.2 The CESR-c Upgrade

Running at all energies from the J/ψ to above the $\Upsilon(4S)$ is possible with existing superconducting interaction region quadrupole magnets. We have already taken modest amounts of data – comparable to some previous data samples – at the $\psi(2S)$ and $\psi(3770)$.

In the Υ region, synchrotron radiation damping reduces the size of beams in CESR and is a crucial factor for achieving high luminosity. This damping will be substantially reduced at the lower energies in the charm threshold region, resulting in serious reduction of luminosity. Much of this luminosity loss can be recovered by installing wiggler magnets (magnets with alternating magnetic field directions) to increase synchrotron radiation. We will use superferric wiggler magnets (Fe poles and superconducting coils). We require a total of 12 of these magnets, each 1.7 m long with 8 poles and maximum field 2.1 T. We designed and built a prototype superferric wiggler and installed it in CESR. In fact we took our low energy $\psi(2S)$ and $\psi(3770)$ data using this wiggler. The wiggler performed as expected and gave us the confidence we needed to proceed with the CESR upgrade. (Not entirely coincidentally, these magnets are excellent prototypes for the damping ring wigglers required in a future linear collider.) The first 6 wigglers will be installed by the end of the current shutdown. These wiggler magnets are the most substantial hardware upgrade in the CLEO-c/CESR-c program.

The luminosity we can achieve in the charm threshold region will still be below that achieved in the Υ region ($\gtrsim 1 \times 10^{33}$ cm^{-2} s^{-1}). We anticipate luminosities ranging from 0.2×10^{33} cm^{-2} s^{-1} at 3.1 GeV to 0.4×10^{33} cm^{-2} s^{-1} at 4.1 GeV.

4 Studying the CLEO-c Physics Reach

Using a fast parameterized Monte Carlo program, we studied the ability of the CLEO-c program to address many of the most important physics questions whose answers may lie in the charm threshold region. The parameters of the program were carefully tuned to match the achieved performance of the CLEO III detector. In the following sections, I summarize a few of the conclusions of these studies. These studies, the performance of the CLEO-c detector, and the CESR upgrade plans are described in much more detail – with comprehensive references – in the CLEO-c/CESR-c project description [2].

5 Hadronic D Decays in CLEO-c

Reconstructing exclusive hadronic decays of D mesons is the foundation of the CLEO-c charm physics program. Hadronic decay modes can be reconstructed very cleanly in the CLEO-c detector as illustrated in Figure 3. Although these modes are the simplest D^0 and D^+ decay modes to reconstruct, we studied much more complicated modes and found that we will also be able to reconstruct many higher-multiplicity modes with very small backgrounds. These exclusive hadronic decays can then be used to tag $D\bar{D}$ events and provide clean samples of D or $\bar{D}$ decays for measuring hadronic decay branching fractions or studying semileptonic and leptonic D decays.

Absolute D branching fractions can be measured by comparing double tag ($D\bar{D}$) rates to single tag (D or $\bar{D}$) rates – a technique pioneered by MARK III [10]. Most systematic errors cancel with this technique and knowledge of production rates is not required. In our Monte Carlo studies we find that double tag events are very clean with little background.

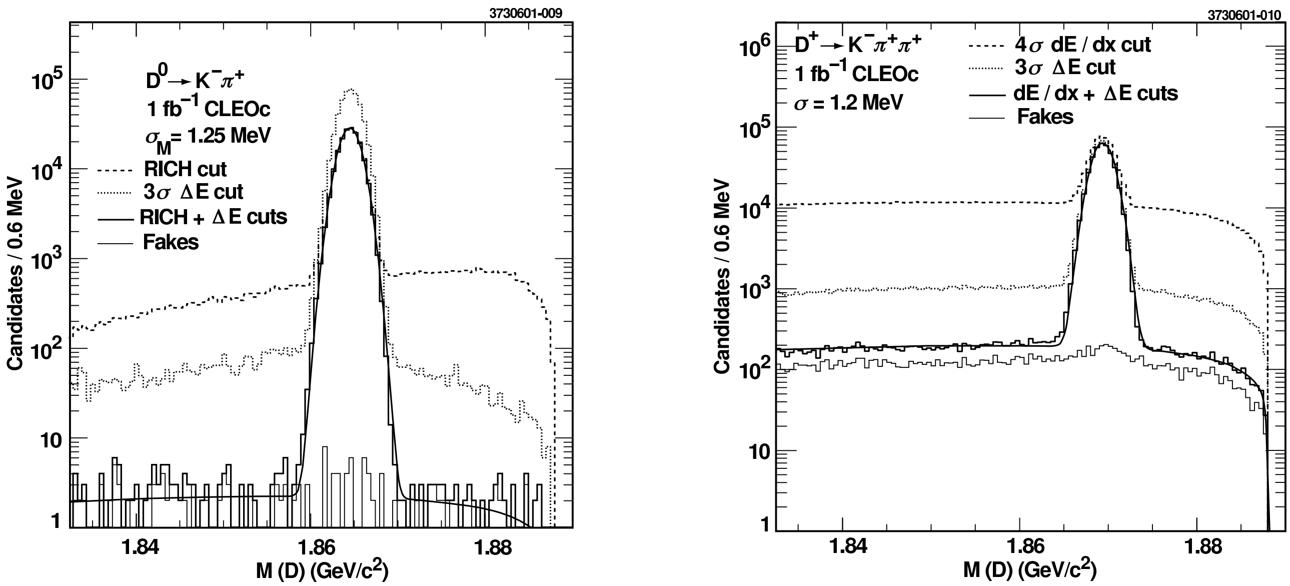

Figure 3. Reconstructed D mass distributions for (left) $D^0 \to K^-\pi^+$ and (right) $D^+ \to K^-\pi^+\pi^+$ decays from Monte Carlo simulations. Note the logarithmic scales, low backgrounds, and that the Monte Carlo samples correspond to only 1 fb^{-1} of data, instead of the anticipated 3 fb^{-1}.

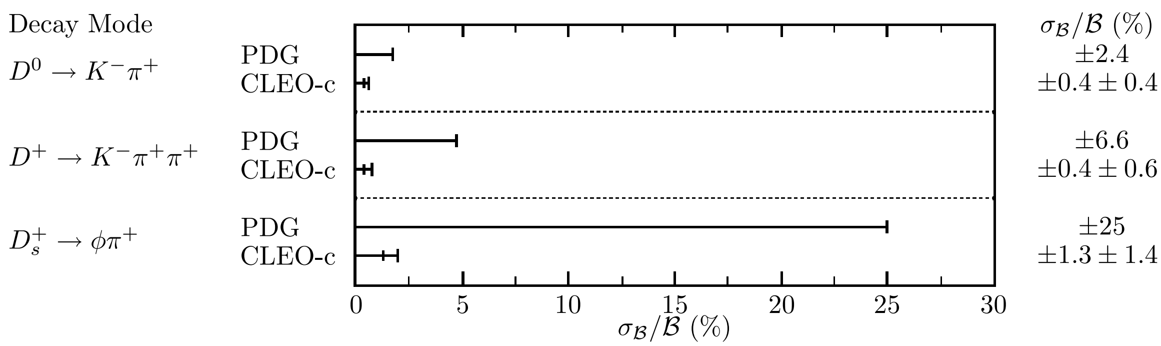

Figure 4. Relative errors in the D meson reference branching fractions. PDG errors are from PDG 2003 and CLEO-c errors are errors expected from CLEO-c.

Table 2. Anticipated single and double tag rates for reference D meson branching fractions and the expected statistical and total errors on the branching fractions. These rates are for the full 3 fb^{-1} CLEO-c data samples.

	Single Tags	Double Tags	Statistical Error	Total Error
D^0	0.54 M	53,000	0.4%	0.6%
D^+	1.14 M	60,000	0.4%	0.7%
D_s^+	0.15 M	6,000	1.3%	1.9%

The hadronic branching fractions, $\mathcal{B}(D^0 \to K^-\pi^+)$, $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$, and $\mathcal{B}(D_s^+ \to \phi\pi^+)$ are the reference branching fractions for all D meson decays. Ultimately they also set the scales of nearly all b and t quark branching fractions. Currently the uncertainty in $\mathcal{B}(D^0 \to K^-\pi^+)$ – the best measured of these – contributes noticeably to the systematic error in measuring $|V_{cb}|$ in $\bar{B} \to D^*\ell^-\bar{\nu}$ decays [7]. We expect tracking efficiency uncertainties to dominate the systematic errors in measuring these branching fractions, and tracking uncertainties will be measured using missing mass techniques. Ultimately we expect tracking efficiency uncertainties to be $\approx 0.2\%$ per track. The CLEO-c single and double tag rates for the reference branching fractions are given in Table 2, and the relative errors expected are compared to those from the PDG [4] in Figure 4.

6 Measuring $|V_{cs}|$, $|V_{cd}|$, and Form Factors in Semileptonic D Decays

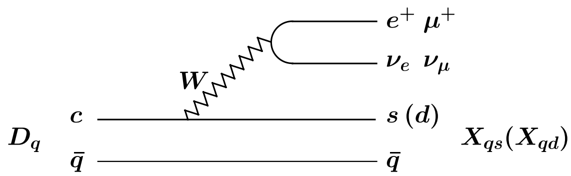

Figure 5. The Feynman diagram for $D \to X\ell\nu$ decays.

Figure 5 illustrates the exclusive semileptonic decays of D^0, D^+, and D_s mesons, where q is u, d, or s for D^0, D^+, or D_s, respectively. The final state particle $X_{qq'}$ will be X_{qs} for Cabibbo favored $c \to sW$ decays and X_{qd} for Cabibbo suppressed $c \to dW$ decays, with CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$, respectively, in the decay amplitude.

Exclusive decays depend on the mass-squared (q^2) of the virtual W through form factors $f(q^2)$. Decay to a pseudoscalar meson ($P_{qq'}$) involves only one form factor, and the differential decay width is given by:

$$\frac{\Gamma(D_q \to P_{qq'}\,\ell^+\nu_\ell)}{dq^2} = \frac{V_{cq'}^2\,p^3}{24\pi^3}\,|f_{qq'}(q^2)|^2 \tag{4}$$

Decay to a vector meson ($V_{qq'}$) involves 3 form factors and a rather more complicated expression involving 3 decay angles (or 3 other variables) in addition to q^2.

All of these form factors are nonperturbative QCD functions, whose q^2 dependence can be measured but whose normalization or absolute value at some point, *e.g.*, $q^2_{\max}$ must be determined from theory. We expect that LQCD will be able to calculate the normalizations of the form factors $f_{qq'}(q^2)$ with precisions of $\mathcal{O}(1\%)$. LQCD should also be able to predict the q^2 dependences of the form factors, so measurements of the q^2 dependences can be used to establish the validity of the LQCD calculations.

In CLEO-c we can detect semileptonic decays in events with a single hadronic tag and an $e^\pm$ accompanied by a hadron $X_{qq'}$ or daughters of its decay. The branching fractions and q^2 dependencies can be measured quite accurately because: rates are high due to high single tag rates and large $D_q \to X_{qq'}\,\ell^+\nu_\ell$ branching fractions, and background rejection from kinematics and particle identification is excellent. We find that the variable $U \equiv E_{\rm miss} - p_{\rm miss}$ (where $E_{\rm miss}$ and $p_{\rm miss}$ are the missing energy and momentum, respectively) can separate signal from background very efficiently. This is illustrated in Figure 6 from a Monte Carlo simulation. Note that even the Cabibbo suppressed decay $D^0 \to \pi^- e^+\nu$ is separated cleanly from the allowed decay $D^0 \to K^- e^+\nu$, whose branching fraction is an order of magnitude larger. Figure 7 illustrates the relative errors expected for a large number of exclusive D meson semileptonic branching fractions and compares these predictions to values found in the current PDG summary [4].

We expect to be able to measure semileptonic branching fractions with errors $\delta\mathcal{B}/\mathcal{B} \lesssim 1\%$ and the exponential slopes (α) of form with errors $\delta\alpha/\alpha \approx 4\%$. These measurements will challenge LQCD theorists to calculate form factors with precisions of $\mathcal{O}(1\%)$. If the challenges are met, CLEO-c measurements of semileptonic D branching fractions will provide values of $|V_{cs}|$ and $|V_{cd}|$ with errors $\lesssim 2\%$. Table 3 shows the contributions of experimental uncertainties to the uncertainties in measuring $|V_{cs}|$ and $|V_{cd}|$ and compares these uncertainties with those from unitarity. Consistency of $|V_{cs}|$ and $|V_{cd}|$ results from many D^0 and D^+ modes and with unitarity will help to verify experimental systematic errors and LQCD calculations of form factors.

7 Measuring f_{D^+} and f_{D_s} in Leptonic D Decays

Figure 1 also illustrates the Feynman diagram for $D_q^+ \to \ell^+\nu_\ell$ decay – where D_q is either D^+ or D_s^+ – if B^+ is replaced with D_q^+. The factor $f_{D_q}V_{cq}$ occurs in the decay amplitude for the $c\bar{q}W$ vertex, and decay widths for leptonic D^+ and D_s^+ decays are given by Equation (2) with M_B replaced by M_{D_q} and $f_B|V_{ub}|$ replaced with $f_{D_q}|V_{cq}|$. Therefore, measurements of $\mathcal{B}(D^+ \to \ell^+\nu_\ell)$ and $\mathcal{B}(D_s^+ \to \ell^+\nu_\ell)$ can be used to determine $f_{D^+}|V_{cd}|$ and $f_{D_s}|V_{cs}|$, respectively. The branching fractions for $D_q^+ \to \ell^+\nu_\ell$ are much larger than the branching fractions for $B^+ \to \ell^+\nu_\ell$, because V_{cq} is much larger than $|V_{ub}|$. Using reasonable guesses for f_{D^+} and f_{D_s} (220 MeV and 260 MeV, respectively) we estimate
$\mathcal{B}(D^+ \to \mu^+\nu_\mu) \sim 4 \times 10^{-4}$ and
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) \sim 6 \times 10^{-3}$.
These branching fractions, the high rates of $D\bar{D}$ production, and high tagging efficiencies all combine to enable precision measurements of $f_{D_q}|V_{cq}|$. Figure 8 illustrates the separation of $D_q^+ \to \mu^+\nu_\mu$ decays from background that can be achieved with tagged samples of D_q decays accompanied by a single μ. The mass $M(\nu)$ of the missing ν is computed from the beam energy, the momentum of the primary tag, and the momentum and energy of the observed μ.

Since we will measure $|V_{cd}|$ and $|V_{cs}|$ accurately with semileptonic D decays, and have unitarity of the CKM matrix to check these values, we can determine f_{D^+} and f_{D_s} with errors $\mathcal{O}(1\%)$. Table 4 shows that f_{D^+} and f_{D_s} can be measured with precisions $\sim 2\%$ with

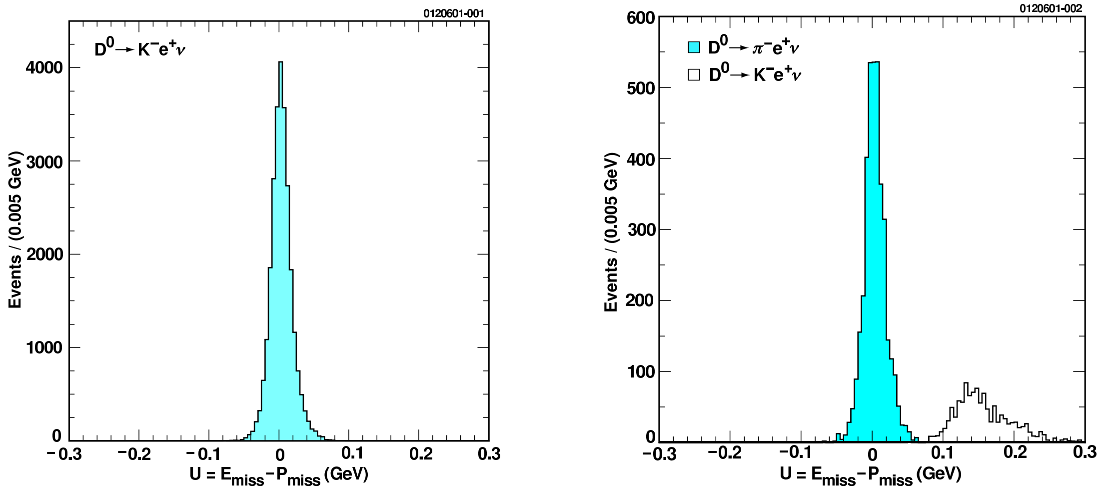

Figure 6. Plots of the U distributions for (left) $D^0 \to K^- e^+ \nu_e$ and (right) $D^0 \to \pi^- e^+ \nu_e$ decays from Monte Carlo samples corresponding to 1 fb^{-1} of data. Note the clean separation of $D^0 \to K^- e^+ \nu_e$ background from the Cabibbo suppressed $D^0 \to \pi^- e^+ \nu_e$ decay sample.

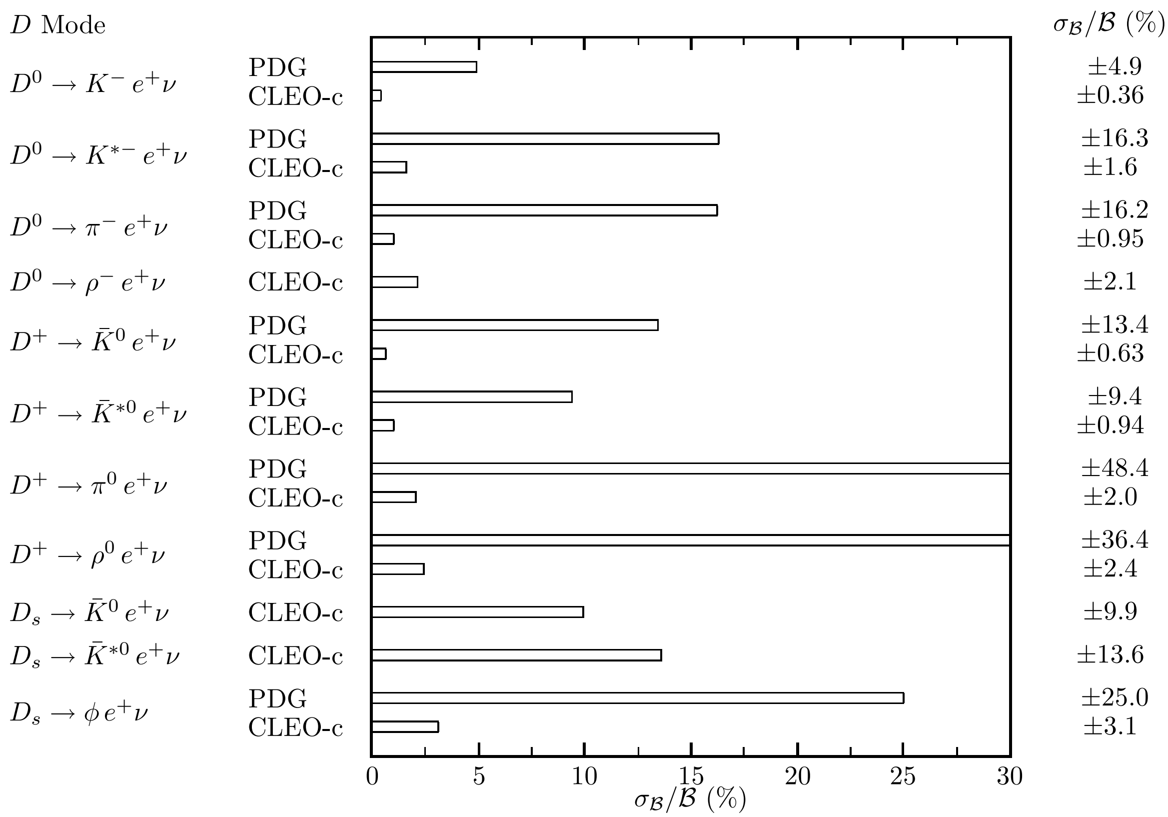

Figure 7. Relative errors in the D meson semileptonic branching fractions. PDG errors are from PDG 2003 and CLEO-c errors are errors expected from CLEO-c.

the full CLEO-c data samples when all sources of uncertainty are taken into account. These measurements will challenge LQCD theorists to compute f_{D^+} and f_{D_s} with uncertainties $\sim 2\%$ and lead to an understanding of the level of reliability of corresponding LQCD f_B calculations. Furthermore, LQCD calculations of the ratio f_B/f_{D^+} are expected to be more reliable than calculations of either f_B or f_{D^+} [11], so precision measurement of f_{D^+} can be used to derive an accurate value of f_B.

8 CKM Element Uncertainties

Figure 9 illustrates the present uncertainties in CKM matrix elements plotted in the ρ-η plane [12] and the uncertainties that could result from the verification

Table 3. Contributions to errors in $|V_{cs}|$ and $|V_{cd}|$ expected from 3 fb^{-1} of $\psi(3770)$ – $D^0\bar{D}^0$ and D^+D^- – CLEO-c data. In this table, $\mathcal{B}$, τ, and ϵ are the relevant branching fractions, lifetimes, and detection efficiencies, respectively.

Decay Mode	V	$\frac{1}{2}(\delta\mathcal{B}/\mathcal{B})$	$\frac{1}{2}(\delta\tau/\tau)$	$\frac{1}{2}(\delta\epsilon/\epsilon)$	$\delta V/V$	Unitarity
$D^0 \to K^-e^+\nu$	$\|V_{cs}\|$	0.2%	0.35%	0.45%	0.6%	0.1%
$D^+ \to \bar{K}^0e^+\nu$	$\|V_{cs}\|$	0.3%	0.6%	0.45%	0.8%	0.1%
$D^0 \to \pi^-e^+\nu$	$\|V_{cd}\|$	0.5%	0.35%	0.45%	0.8%	1.1%
$D^+ \to \pi^0e^+\nu$	$\|V_{cd}\|$	1.0%	0.6%	0.45%	1.3%	1.1%

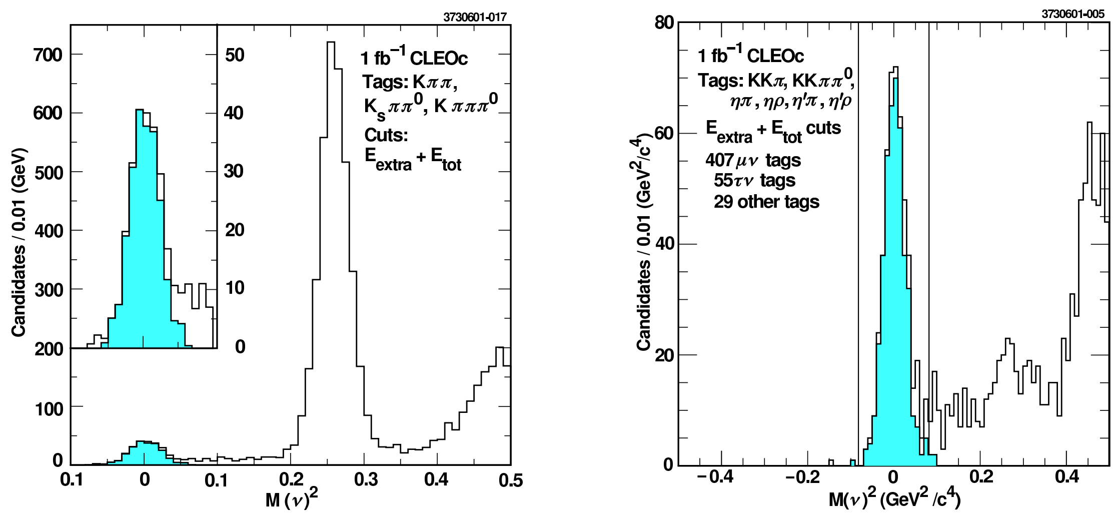

Figure 8. Plots of the $M(\nu)^2$ distributions for (left) $D^+ \to \mu^+\nu_\mu$ and (right) $D_s \to \mu^+\nu_\mu$ decays. These Monte Carlo simulations correspond to 1 fb^{-1} of data, not the expected 3 fb^{-1}.

Table 4. Contributions of the major uncertainties to errors in f_{D^+} and f_{D_s} expected from 3 fb^{-1} each of D^+D^- and $D_s^+D_s^-$ CLEO-c data. In this table, $\mathcal{B}$ and τ are the relevant branching fractions measured in CLEO-c and the lifetimes, respectively. The last column gives the uncertainties from the current PDG summary.

Decay Mode	Signal	Bkg	$\frac{1}{2}(\delta\mathcal{B}/\mathcal{B})$	$\frac{1}{2}(\delta\tau/\tau)$	$\delta\|V_{cq}\|/\|V_{cq}\|$	$\delta f_{D_q}/f_{D_q}$		PDG
$D^+ \to \mu^+\nu$	672	90	1.9%	0.6%	1.1%	2.3%	f_{D^+}	—
$D_s^+ \to \mu^+\nu$	1,221	252	1.4%	1.0%	0.1%	1.7%	f_{D_s}	35%
$D_s^+ \to \tau^+\nu$	1,740	114	1.2%	1.0%	0.1%	1.6%	f_{D_s}	60%

of LQCD calculations by CLEO-c. The top plot uses current experimental uncertainties and quite conservative current theoretical uncertainties. An up-to-date overview of uncertainties of CKM parameters in the ρ-η plane can be found in these proceedings [13]. The bottom plot use the same experimental uncertainties but theoretical uncertainties of $\mathcal{O}(1\%)$; in particular, uncertainties of 2% for decay constants and bag parameters, and 3% for semileptonic form factors. It is clear that the CLEO-c program can have a substantial impact on our understanding of the CKM matrix.

Other experimental programs can also contribute significantly to precision measurements of CKM matrix elements:

- BEPCII and BESIII
  BEPCII will be a new e^+e^- collider in Beijing operating in the charm threshold region with anticipated luminosity at least three times that of CESR-c. Many capabilities of the proposed BESIII detector are comparable to that of the CLEO-c detector. The Chinese government approved the BEPCII proposal in February and the Beijing group expects to turn on in about 5 years.

- BaBar, BELLE, and FOCUS
  Absolute D branching fractions are hard to measure in the Υ region or at Fermilab. However, precision measurements of the ratios of branching fractions and the q^2 dependence of form factors

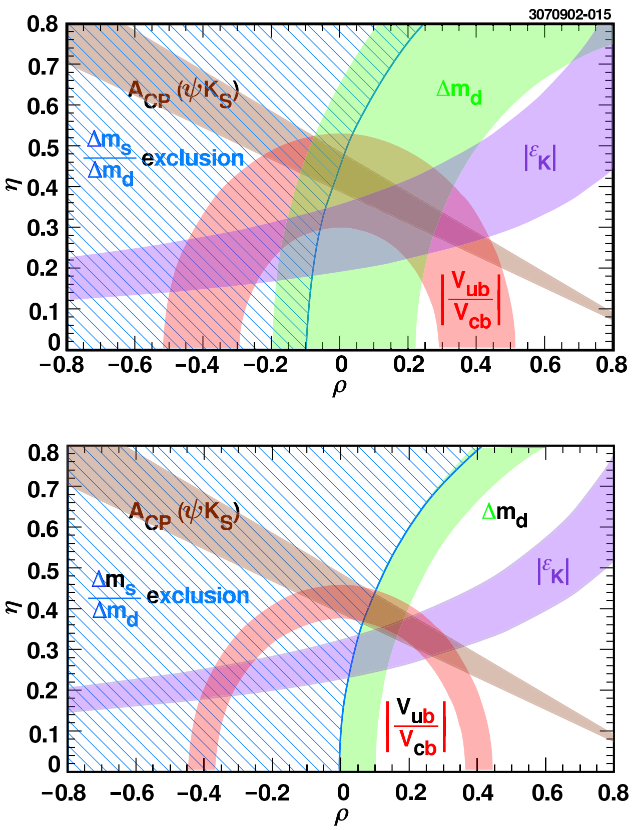

Figure 9. Plots of allowed regions in the ρ-η using current experimental measurements and (top) quite conservative current theoretical uncertainties and (bottom) theoretical uncertainties resulting from the CLEO-c program and improved LQCD calculations. Note that the improvement in the ε_K band will not result directly from the effect of CLEO-c measurements on LQCD, but from more general progress in LQCD.

in semileptonic decays can constrain CLEO-c and BESIII results. Improved measurements of charm lifetimes will also be important if BESIII is able to reduce systematic errors substantially below those of CLEO-c.

9 Summary and Outlook

Nonperturbative QCD parameters are needed to extract $|V_{cb}|$, $|V_{ub}|$, and $|V_{td}|$ from B physics measurements. Even with CLEO's luminosity, residual theoretical uncertainties are already comparable to experimental errors. Substantial theoretical progress will be required in order to fully benefit from the large luminosities being accumulated by BaBar and Belle. In the D meson sector, CLEO-c can measure absolute branching fractions, semileptonic decays, and leptonic decays ($D \to \bar{\ell}\nu$) with $\sim 1\%$ precision.

This program can motivate Lattice QCD theorists to attempt to reach comparable precision in calculating the nonperturbative QCD parameters involved in these D decay measurements – particularly semileptonic decay form factors and $f_{D_{(s)}}$. Success in this program will build confidence in applying these calculations to the B sector for measurements of $|V_{cb}|$, $|V_{ud}|$, and $|V_{td}|$. CLEO-c and (later) BESIII will likely dominate absolute branching fractions measurements. FOCUS, BaBar, and BELLE have contributed or will contribute significantly to charm lifetimes, relative branching fractions and form factor measurements, and searches for new physics.

As the CLEO-c and LQCD programs gain momentum, we can expect very fruitful interactions between theory and experiment leading to substantial improvements in our knowledge of CKM matrix elements.

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